HH combination results from the CMS experiment

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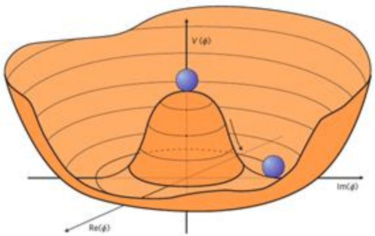
SM Higgs potential and self-couplings

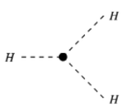
- The Higgs self-couplings are still largely unconstrained experimentally
- The couplings provide key information on the shape of the Higgs potential *V(H)*
- Known m_H (~125 GeV), SM predicts $\lambda_3 = m_H^2 / 2v^2$ (~0.13).
- $\lambda_3 = \lambda_4$ in the SM



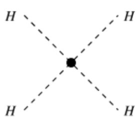
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

Mass term

Higgs trilinear self-coupling



Higgs quartic self-coupling



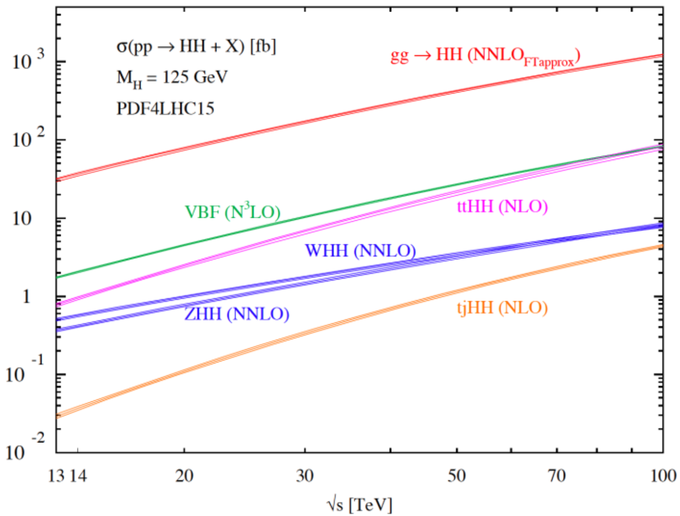
$$m_H = \sqrt{2\lambda v^2}$$

$$v = 246\ GeV$$

$$\kappa_\lambda = \lambda_3 / \lambda_3^{SM}$$

- λ_3 directly accessible through the production of Higgs boson pairs
- Contributions also come from single Higgs production via NLO EW corrections
- λ_4 out of reach of the LHC

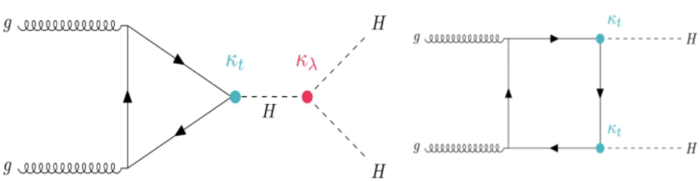
SM HH production cross sections at the LHC



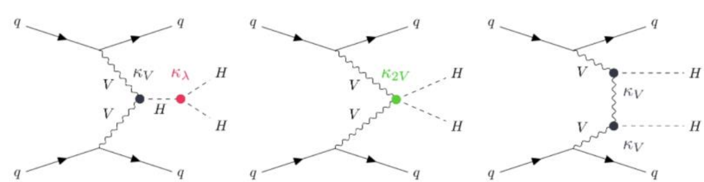
$\sqrt{s}$	13 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$
VBF HH	$1.73^{+0.03\%}_{-0.04\%} \pm 2.1\%$
ZHH	$0.363^{+3.4\%}_{-2.7\%} \pm 1.9\%$
W^+HH	$0.329^{+0.32\%}_{-0.41\%} \pm 2.2\%$
W^-HH	$0.173^{+1.2\%}_{-1.3\%} \pm 2.8\%$
$t\bar{t}HH$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$
$tjHH$	$0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$

in fb

Gluon-gluon fusion (ggF)



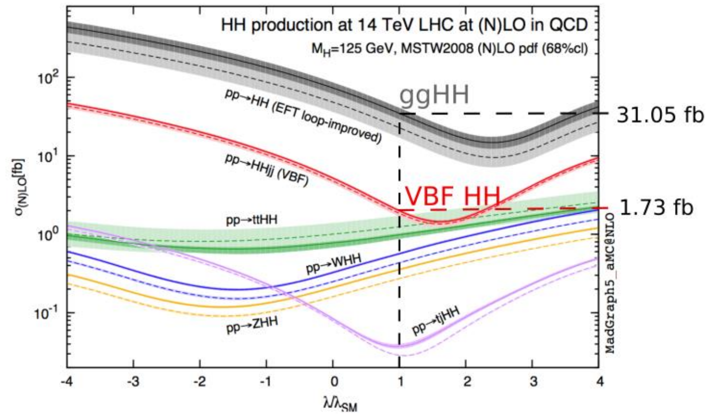
Vector Boson fusion (VBF)

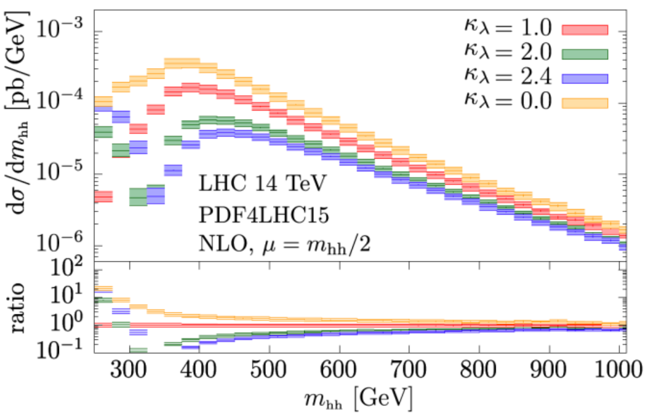


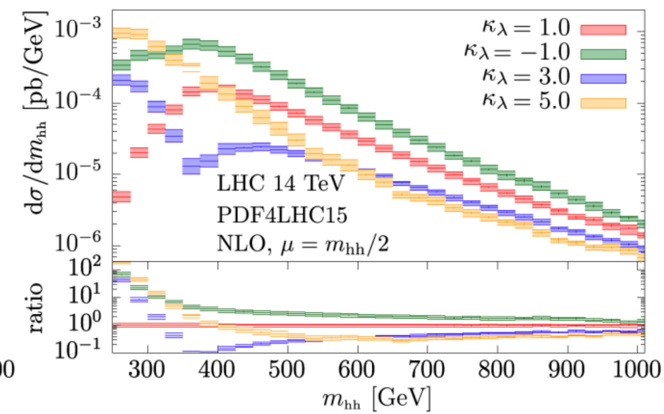
Destructive interference!

HH cross section as a function of k_λ

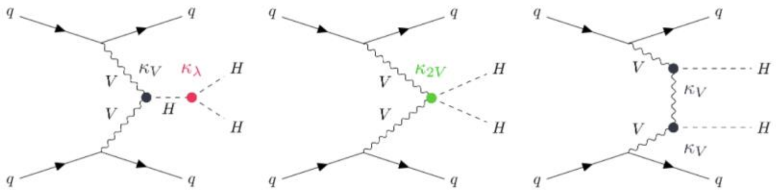
- The HH production allows us to search for new physics ($k_\lambda \neq 1$)
- HH cross section is a quadratic function of k_λ
- $k_\lambda \approx 2.4 \rightarrow$ max interference of ggF diagrams
- At large | k_λ |: softer m_{HH} spectra and larger cross section values
- At medium | k_λ |: hard spectra $\rightarrow$ enhanced boosted signatures

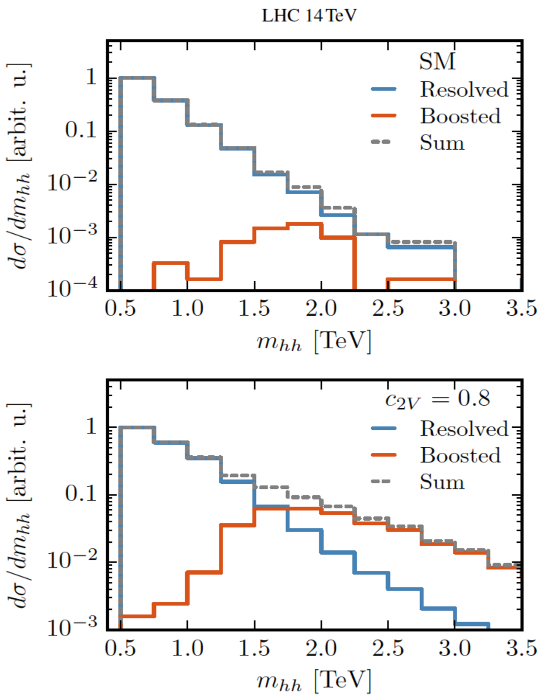






VBF HH cross section: constraint on k_{2V}





- The Higgs self-coupling k_λ
- The Higgs-vector-boson coupling (VVH) k_V
- The quartic coupling (VVHH) k_{2V}
  - VBF HH mode provides a unique handle to probe k_{2V}
  - If the VVHH coupling deviates from the SM ($k_{2V} \neq 1$), the cross section can be enhanced
  - In BSM scenarios with modified couplings ($k_{2V} \neq 1$, $k_V \neq 1$), a significant fraction of signal becomes boosted

↓

decay products merged into large-R jets

Public HH results

- ***HH → bbbb***
Phys. Rev. Lett. 129,081802

- *HH → bbbb boosted (ggF and VBF)*
Phys. Rev. Lett. 131,041803

- *HH → bbtt*
Phys. Rev. Lett. 842 (2023) 137531

- *HH → bb$\gamma\gamma$*
JHEP03(2021)257

- *HH → bbZZ(4l)*
JHEP06(2023)130

- *HH → WWW*W*,WW$\tau\tau$, $\tau\tau\tau\tau$, multileptons*
JHEP07(2023)095

- *HH Run2 combination*
Nature vol. 607, pages 60–68 (2022)

- ***HH → WW$\gamma\gamma$***
CMS-PAS-HIG-21-014

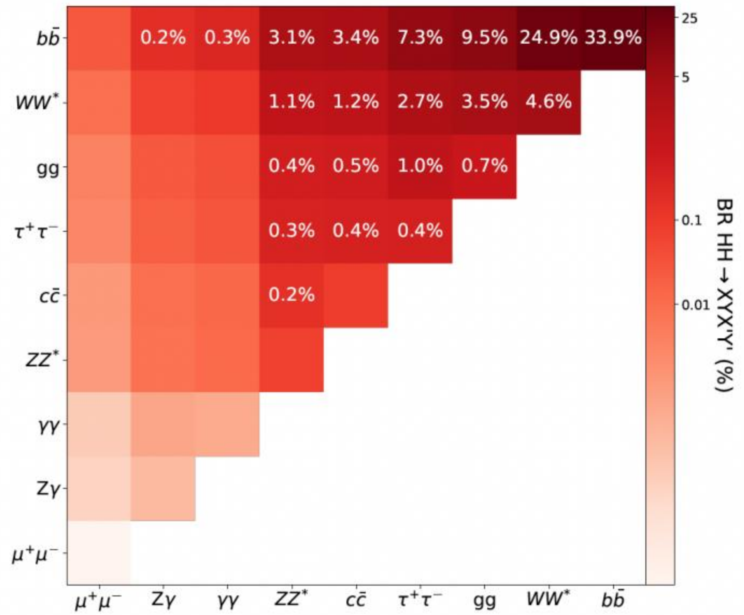
- *HH → bbWW*
CMS-PAS-HIG-21-005

- *VHH → 4b*
CMS-PAS-HIG-22-006

HH decay channels

- The sensitivity to HH production is mainly due to:
  - HH → bbbb
  - HH → bbVV
  - HH → bbττ
  - HH → bbγγ

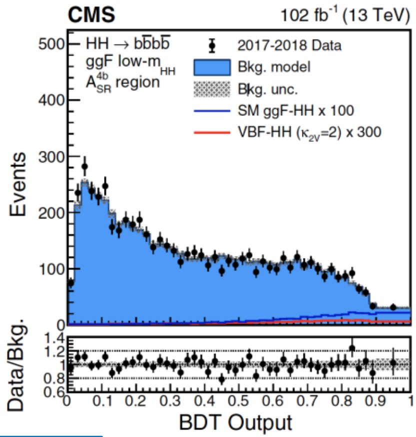
- Necessity to find a good compromise in terms of signal/noise ratio
  - → Not too high background contamination
  - → Not too low σ·BR



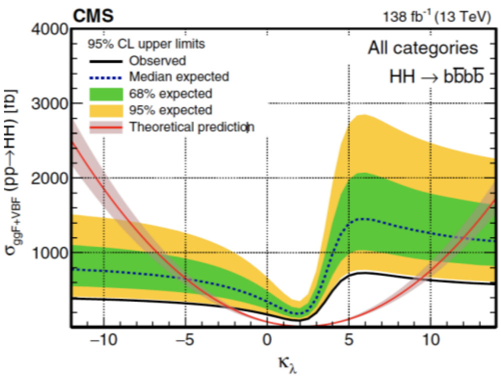
Branching fractions for the decay of an HH pair (@m_H=125.0 GeV/c^2)

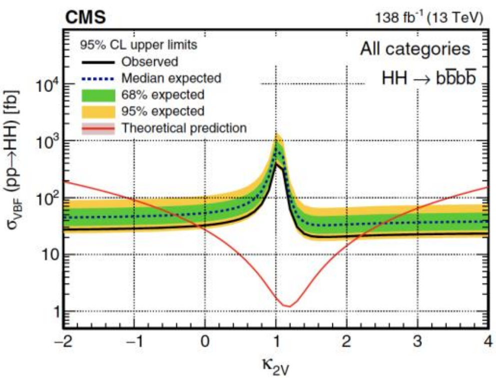
HH→bbbb (resolved)

- Higher BR
- Large multi-jets background.
- BDT to improve the purity of signal/bkg categories.
- BDT score distribution → input for the statistical analysis.
- ggF + VBF: $\sigma^{95\%}/\sigma_{SM}$ obs. (exp.) = 3.9 (7.8)
- Likelihood scan for different values of k_λ , k_{2V} → intervals



Obs. (exp.) constraint @ 95%CL:
$-2.3 < k_\lambda < 9.4$ ($-5.0 < k_\lambda < 12.0$)
$-0.1 < k_{2V} < 2.2$ ($-0.4 < k_{2V} < 2.5$)





HH→bbbb (boosted)

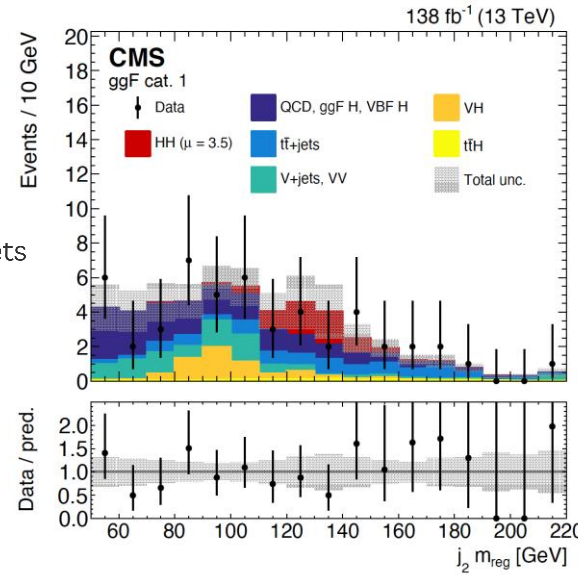
ggF and VBF HH→4b decay where both H have large p_T > 300 GeV in the boosted regime

Benefits of the boosted strategy

- Enhanced sensitivity for anomalous couplings
- Less combinatorics than in resolved topology
- Small background from the tails of SM processes

Analysis strategy

- Reconstruct H→bb decay products as anti-k_t ΔR=0.8 jets
- 2 highest-p_T anti-k_t =0.8 ΔR=0.8 jets as Higgs cands
- ParticleNet Jet tagger algorithm
- VBF topology: two anti-kt 4 jets with large dijets mass and Δη;
- ggF topology by vetoing the VBF one
- Obs. (exp.) 95% UP on HH production : 9.9 (5.1) x SM



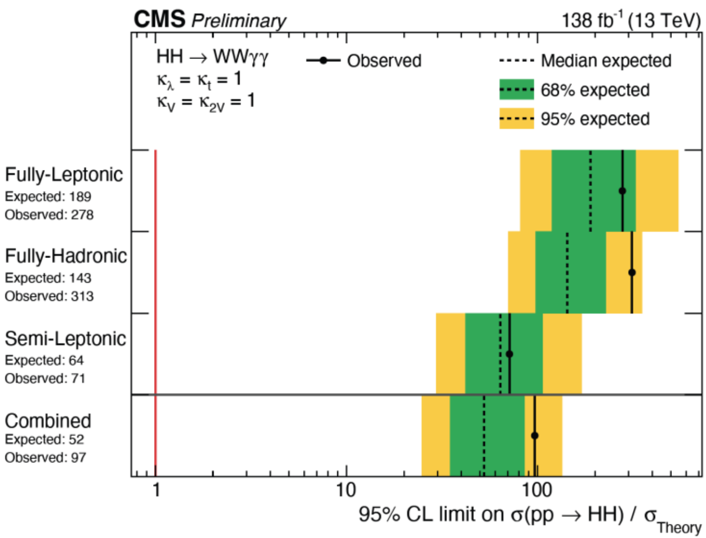
Assuming $k_\lambda = k_t = k_V = 1$, the obs. (exp.) constraint @95%CL:
$0.62 < \kappa_{2V} < 1.41$ $(0.66 < \kappa_{2V} < 1.37)$
The strongest constraint on κ_{2V} so far.

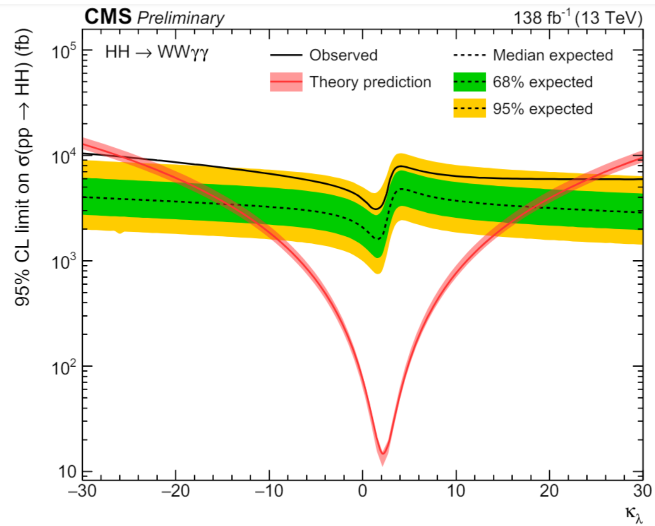
→

The hypothesis k_{2V}=0 (with other couplings equal to 1), is excluded at a CL higher than 99.9%.

CMS: HH→WWγγ

- A narrow peak in $\gamma\gamma$ mass
- 3 final states depending on the W bosons decays
  1) Fully-hadronic (4q gg) → DNN
  2) Semi-leptonic (2q ln gg) → DNN
  3) Fully-leptonic (2l 2n gg) → cut based





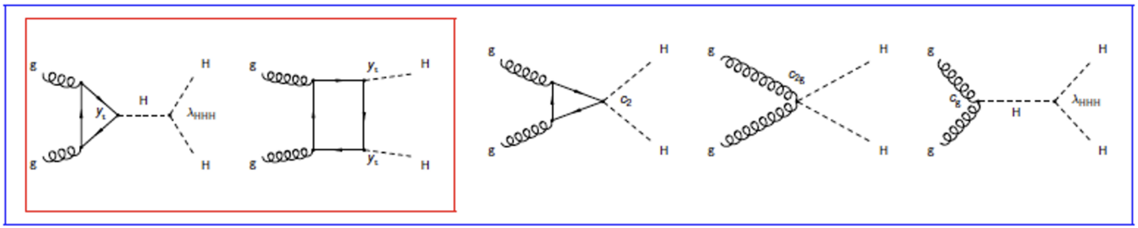
- Backgrounds: H, HH→ $bb\gamma\gamma$
- Obs. (exp.) UL @95%CL on signal strength: 96.8 (52.5)

Obs. (exp.) constraint @ 95%CL:
$-25.8 < k_\lambda < 24.1$ ($-14.4 < k_\lambda < 18.3$)

CMS: HH→WWγγ: HEFT

HEFT ggF cross section modeling with three new contact interactions: ttHH (C_2), ggHH (C_{2g}), ggH (C_g)

SM ($k_\lambda=1$, $k_t=1$, $c_{2g}=c_g=c_2=0$) **BSM**

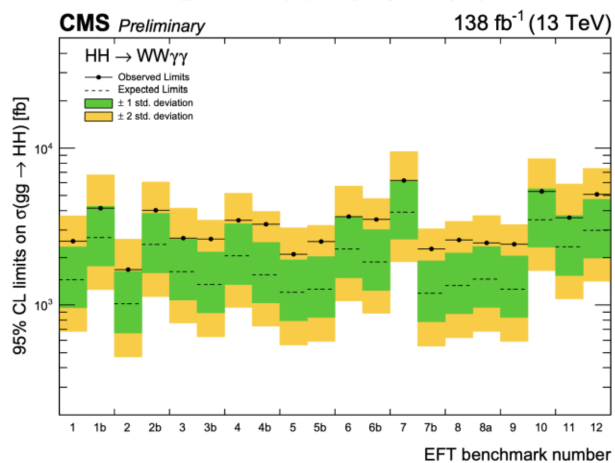


$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - k_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}(v + k_t h + \frac{c_2}{v} hh)(\bar{t_L} t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}(c_g h - \frac{c_{2g}}{2v} hh) G^{\mu\nu} G_{\mu\nu}$$

JHEP 09 (2018) 057
JHEP 04 (2016) 126
JHEP 03 (2020) 091

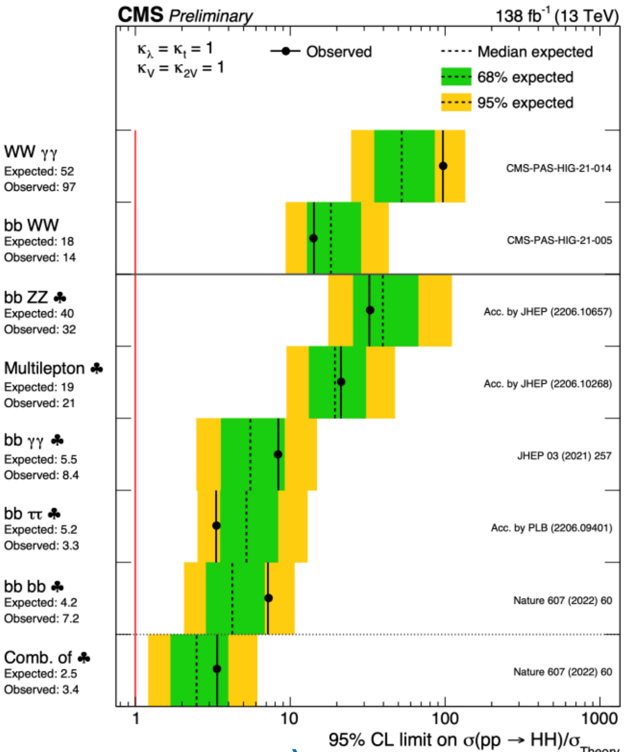
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
1b	3.94	0.94	$\frac{-1}{3}$	0.75	-1
2b	6.84	0.61	$\frac{1}{3}$	0.0	1.0
3b	2.21	1.05	$\frac{-1}{3}$	0.75	-1.5
4b	2.79	0.61	$\frac{1}{3}$	-0.75	-0.5
5b	3.95	1.17	$\frac{-1}{3}$	0.25	1.5
6b	5.68	0.83	$\frac{1}{3}$	-0.75	-1.0
7b	-0.10	0.94	1.0	0.25	0.5

Ranging from 1.7 - 6.2 (1.0 - 3.9) pb

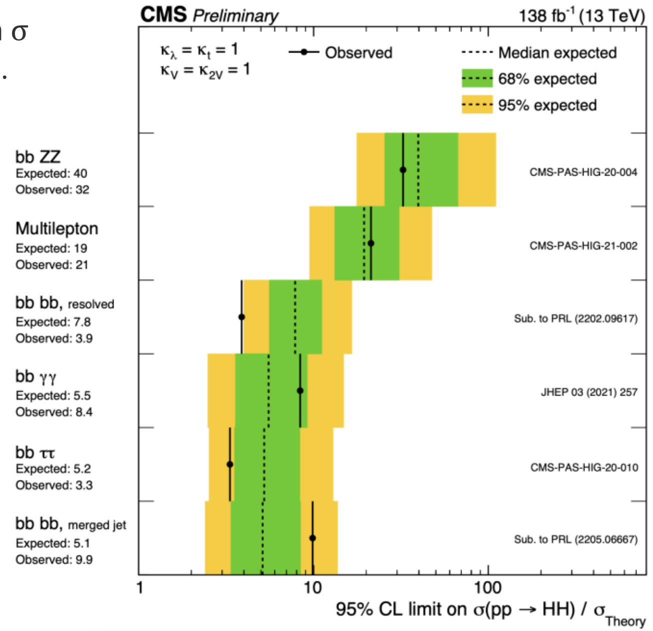


HH combination: 95% C.L. limits on the signal strength

The observed (expected) combined 95%CL UL on σ is found to be 3.4 (2.5) times the SM prediction.



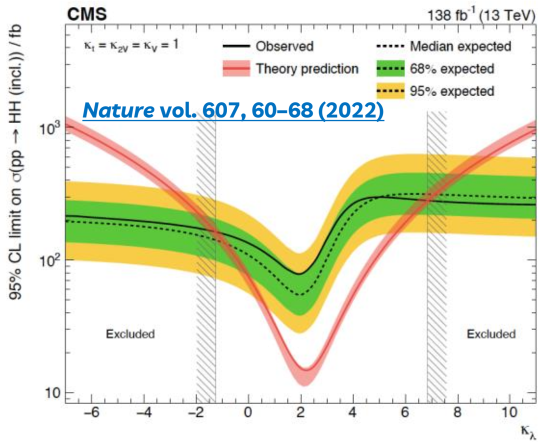
[Nature vol. 607, 60–68 (2022)]

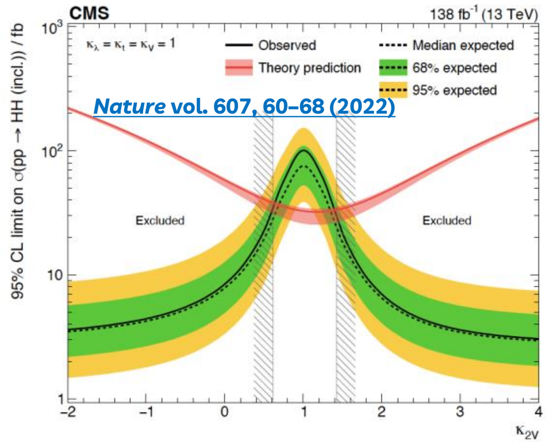


Improvements w.r.t combination with 2016 data only due to:

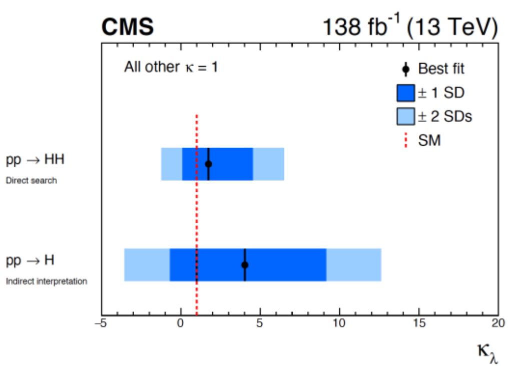
- Detector upgrades
- CMS reconstruction & object tagging
- Improved analysis techniques
- Addition of new channels

HH combination: constraint @95%C.L. on k_λ and k_{2V}





- Obs. (exp.) constraint @ 95%CL: $-1.24 < k_\lambda < 6.49$ ($-2.28 < k_\lambda < 7.94$)
- Significance for excluding $k_{2V} = 0$

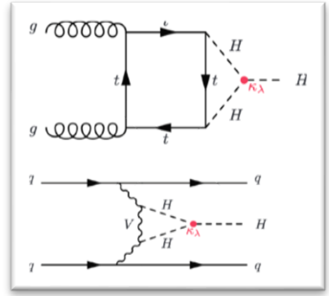


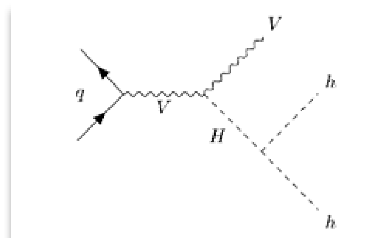
CMS excluded $k_{2V} = 0$ with 6.6σ assuming SM values of other k's.

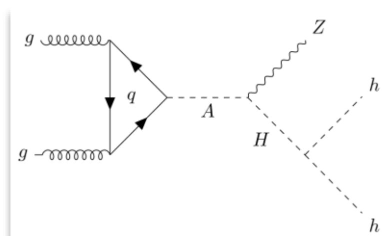
Quartic VVHH coupling estabilished for the first time!

Future perspectives

- Combination of H and HH results
- Adding more statistics to improve the sentisivity to the SM (Run2 + Run3 data)
- Combination of ATLAS and CMS results
- Adding the contribution of new analyses
- Get prepared to HL-LHC → possible observation of HH!
- Probe some BSM scenarios:\
  - HEFT (search for a general parametrization of the cross-section as function of the 5 HEFT couplings)
  - Perform resonant analyses (VHH)







Thanks!